IAC-12. A2.7.4

COMBUSTION, COMPLEX FLUIDS, AND FLUID PHYSICS EXPERIMENTS ON THE ISS

Brian J. Motil
NASA Glenn Research Center, Cleveland, Ohio, USA

David L. Urban
NASA Glenn Research Center, Cleveland, Ohio, USA

From the very early days of human spaceflight, NASA has been conducting experiments in space to understand the effect of weightlessness on physical and chemically reacting systems. NASA Glenn Research Center (GRC) in Cleveland, Ohio has been at the forefront of this research looking at both fundamental studies in microgravity as well as experiments targeted at reducing the risks to long duration human missions to the moon, Mars, and beyond.

In the current International Space Station (ISS) era, we now have an orbiting laboratory that provides the highly desired condition of long-duration microgravity. This allows continuous and interactive research similar to Earth-based laboratories. Because of these capabilities, the ISS is an indispensible laboratory for low gravity research. NASA GRC has been actively involved in developing and operating facilities and experiments on the ISS since the beginning of a permanent human presence on November 2, 2000. As the lead Center for combustion, complex fluids, and fluid physics; GRC has led the successful implementation of the Combustion Integrated Rack (CIR) and the Fluids Integrated Rack (FIR) as well as the continued use of other facilities on the ISS. These facilities have supported combustion experiments in fundamental droplet combustion; fire detection; fire extinguishment; soot phenomena; flame liftoff and stability; and material flammability. The fluids experiments have studied capillary flow; magneto-rheological fluids; colloidal systems; extensional rheology; pool and nucleate boiling phenomena. In this paper, we provide an overview of the experiments conducted on the ISS over the past 12 years.

INTRODUCTION AND BACKGROUND

NASA's Physical Science Research Program, along with its predecessors of the last 50 years, have made significant contributions in two distinct thrusts. The first is fundamental research, which is investigating physical phenomena in the absence of gravity and fundamental laws of the universe to provide new scientific knowledge and societal benefit. These experiments were conducted on a wide array of platforms from earth-based to space-based. The second field is applied research, which contributes to the basic understanding underlying space exploration technologies such as power generation and storage, space propulsion, life support systems, fire safety, and environmental monitoring and control. Both have led to improved space systems or produced new products on Earth. The program benefits from research collaborations with several of the ISS international partners (Europe, Russia, Japan and Canada) and individual foreign governments with space programs, such as France, Germany and Italy.

NASA's physical science research is organized into five disciplines—complex fluids, fundamental physics, fluid physics, combustion science and materials science. Conducted in a nearly weightless environment, experiments in these disciplines reveal how physical systems respond to the near absence of buoyancy-driven convection, sedimentation or sagging. They reveal how other forces, such as capillary forces, which are small compared to gravity, can dominate the system behavior in space. Examples of observations in space include boiling in which bubbles do not rise, colloidal systems containing crystalline structures unlike any seen on Earth, circular flames burning around fuel droplets, flame spread measurements at very low flow rates, directional solidification of metal alloys producing a uniformly aligned microstructure that improves material properties, and fluids flowing in relatively wide channels without the use of a pump.

In the current ISS era, we now have an orbiting laboratory that provides the highly desired condition of long-duration microgravity. This allows continuous and interactive research similar to Earth-based laboratories, even providing statistical validity when required. Because of these capabilities, the ISS is an indispensible laboratory for low gravity research.

Here we describe the experiments that have been conducted or are underway on the ISS in combustion science, complex fluids, and fluid physics.

COMBUSTION SCIENCE

Despite being the subject of active research for over 80 years, combustion processes remain one of the most poorly controlled phenomena that have a significant impact on human health, comfort and safety. This is because the simplest combustor (e.g. kitchen stove) remains beyond our detailed numerical modeling capabilities. This is a result of the large number of chemical reactions that must be modeled (hundreds), and the strong complications imposed by buoyancy.

The NASA ISS Combustion and Reacting Systems Discipline is organized to provide a more complete understanding of the fundamental controlling processes

through microgravity testing. Microgravity provides simpler one-dimensional systems that include:

- removal of the complex interaction between the buoyant flow and the energy feedback to the flame,
- realistic simulation of the fire risk seen in manned spacecraft;
- practical simulation of the gravitational environment seen for reacting systems in future spacecraft

Droplet Combustion

The availability of a long-duration, high quality microgravity environment allows researchers to study the textbook problem of a spherical droplet surrounded by a spherical flame in an infinite, quiescent ambient atmosphere. A cadre of researchers from academia, industry and federal laboratories has successfully established this simple geometry as an excellent test bed to study fundamental combustion science problems and other topics of applied combustion research.

The key element to all of these programs was the necessity of a high-quality microgravity environment. Most importantly, they provided long-duration ground-based facilities where compromises to experiment integrity were minimized.

The droplet combustion community is fortunate to currently have the Combustion Integrated Rack (CIR) and Multi-User Droplet Combustion Apparatus (MDCA), CIR insert, available to study droplet combustion aboard the International Space Station (ISS). This facility is currently operational and allows the dispensing, deployment and ignition of droplets ranging in size from 1 to 5 mm (either free-floating or fiber-supported) in a 0–3 atm ambient environment of up to 40 percent oxygen (balance of a range of inert gases and inert gas mixtures).

Flame Extinguishment Experiment (FLEX)

The Flame Extinguishment Experiment (FLEX) uses the CIR with the objective of the study of heptane and methanol droplets in ambient mixtures of oxygen and nitrogen diluted with a second inert gas (nitrogen, carbon dioxide, helium and xenon). The goal of the research is to examine how the addition of an inert gas suppressant influences the flammability limit of the two fuels. The application is an improved quantitative understanding of how flammability limits change in reduced gravity. The research to date shows that the flammability limit is lower in reduced gravity. The implication of this result is that terrestrial standards for inert gas suppressants in low gravity do not offer the same margin of safety as in normal gravity.

The FLEX experiments are of interest for terrestrial applications as well. The physical and chemical kinetic models of heptane and methanol combustion are the building blocks for more complex models of practical liquid fuels such as diesel and jet fuel. The long-duration experiments on the ISS provide benchmark data that researchers can develop, improve, and ultimately validate detailed theoretical and numerical models of liquid hydrocarbon fuel combustion. The FLEX experiments performed to date demonstrated radiative and diffusive extinction, combustion instabilities, lower flammability limits and unexplained vaporization after visible flame extinction. Comparison with theoretical and numerical models validated aspects of the models while identifying areas that require improvement. Recently the FLEX experiment released novel results which demonstrated the possible existence of cool-flame chemistry in a stable flame that does not transition to a hot-flame [1]. This behavior has not been previously reported.

FLEX-2, the follow-on experiment, builds upon FLEX. It studies a range of fuels including mixtures of pure fuels, real fuel surrogates, soot formation, slow sub-buoyant convective flow effects, and droplet-droplet interactions. International collaborations extend this to study flame propagation in droplet arrays, and investigate the combustion of liquid biologically-derived fuels.

Gaseous Diffusion Flames

Smoke Point In Coflow Experiment (SPICE)

The Smoke Point In Coflow Experiment (SPICE) was conducted in 2009 on the International Space Station in its Microgravity Science Glovebox (MSG) and studied laminar, axisymmetric, gas-jet diffusion flames [2]. The object of the SPICE experiment is to investigate the transition to soot emission in gas-jet flames. The smoke-point is a result of the fuel chemistry and flow conditions, and is an effective indicator of the propensity of a fuel to emit light and to produce soot. Soot control remains one of the major unsolved problems in combustion. Simple predictions of soot emission are the major goal of the SPICE experiment.

Structure & Liftoff In Combustion Experiment (SLICE)

The SLICE experiment investigates the structure of lifting and lifted flames, where flow conditions and the combustion chemistry cause the flame to detach from the burner and stabilize at a downstream position. The twin purposes for the SLICE research are increased fuel efficiency and reduced pollutant emission in practical combustion devices. More explicitly, the experiment is being conducted to advance combustion modeling

capability, which "allows system designers to improve efficiency and reduce harmful pollutants in ways never before possible" (as stated by an external reviewer of the SLICE experiment). SLICE will be carried out using the Smoke Point In Coflow Experiment (SPICE) hardware in the Microgravity Science Glovebox (MSG) and is a precursor to the Coflow Laminar Diffusion Flame (CLD Flame) experiment that is now in development for the ISS Combustion Integrated Rack (CIR) as part of the Advanced Combustion via Microgravity Experiments (ACME) project.

Spacecraft Fire Safety

Spacecraft fire detection provides significant challenges compared to terrestrial conditions because the properties of the smoke emitted from fires is affected by buoyancy. The conditions on a spacecraft require rapid detection of fires with limited false alarms. Two recent experiments examine issues related to spacecraft fire detection. The Dust Aerosol measurement Feasibility Test (DAFT) [3] examined the background aerosol particulate levels on the ISS. The Smoke Aerosol Measurement Experiment (SAME) [4] examined the particle size distribution of the smoke from spacecraft materials. These instruments can provide useful guidance for the designers of future spacecraft smoke detectors.

Solid Fuel Combustion/Material Flammability

Space-based and ground-based low gravity experiments in material flammability have revealed substantial differences in the behavior of flames over solid materials in reduced gravity. Many of these observations have specific impact on the hazard of spacecraft fires in addition to being of fundamental solid fuel combustion importance. Microgravity experiments demonstrated that the assumed margin of safety of reduced flammability in microgravity, based on quiescent test results, is not valid for most spacecraft environments where ventilation flow strongly enhances flames. In the low flow conditions of microgravity or partial gravity, some materials are flammable at lower oxygen concentrations than in normal gravity. Materials are easier to ignite in low gravity due to reduced convective cooling from the fuel surface. Once established, flames in low-speed air flows preferentially spread into the oncoming air flow. This is opposite to the effect that occurs in normal gravity. Radiant heat transfer was shown to substantially affect the material's flammability. Surface radiative heat loss reduces the flammability, but an external radiative heat flux can cause materials to ignite and spread faster.

Burning and Suppression of Solids (BASS)

The Burning and Suppression of Solids (BASS) investigation has been conducted in the Microgravity Science Glovebox examining the burning and extinction characteristics of a wide variety of fuel samples in microgravity. The BASS experiment will guide strategies for extinguishing accidental fires in microgravity. BASS results contribute to the limited database of solid combustion in microgravity. In addition, BASS will guide combustion computational models used in the design of fire detection and suppression systems in microgravity and on Earth.

BASS tests the hypothesis that materials in microgravity, with adequate ventilation, burn as well if not better than the same material in normal gravity with other conditions being identical (pressure, oxygen concentration, temperature, etc.). The fuel is ignited, and the air flow speed is the main variable. After some time, selected flames will be intentionally extinguished by applying a suppressant. There are important differences in the suppression of fires in space compared to on Earth. On Earth it is understood that the best results are generally obtained when the extinguisher "attacks" the base of the flame, which is both the stabilization point and the point where fresh air first enters the flame. For a fire burning in microgravity, the best point of application of suppressant may not be immediately apparent, especially for a partially obstructed flame or a wake-stabilized flame. Depending on the geometry of the flame and the characteristics of the extinguisher (distance from flame, dispersion angle) it is possible that the suppressant stream will be ineffective or might actually make the flame worse through the entrainment of oxygen. Using nitrogen as a flame suppressant in microgravity provides a direct link to current and planned extinguishment techniques.

The significance of BASS will be to improve NASA fire safety strategies for spacecraft. The current NASA spacecraft materials selection is based on a standard test method (NASA–STD–6001 Test 1) that segregates material based on 1-g behavior without consideration of low gravity effects. A critical element of this understanding is the radiative heat emission from the flame. These results are used in first order models and predictions of heat release in spacecraft fires and as a means to extend heat release data from tests like the NASA cone calorimeter test (NASA–STD–6001 Test 2) to a performance-based material selection process. Using nitrogen as a flame suppressant in microgravity provides a direct link to current and planned extinguishment techniques.

In addition, BASS results provide essential guidance to ground-based microgravity combustion research efforts. Detailed combustion models are validated using the simpler flow environment afforded by tests in microgravity. Once validated, they can be used to build

more complex combustion models needed to capture the important details of flames burning in normal gravity. These models have wide applicability to the general understanding of many terrestrial combustion problems.

COMPLEX FLUIDS

Complex fluids comprise a large class of soft materials including colloids, micro-emulsions; foams; liquid crystals; and granular material. It is possible to study these systems and gain insight into many diverse fields such as phase transitions, nucleation and crystal growth, glass formation, chaos, field theory, and much more. Furthermore, research in complex fluids provides the underpinnings of applications related to NASA exploration of planetary surfaces as well as terrestrial applications in industries such as pharmaceutical, chemical, plastics, petroleum, electronics, and liquid-crystals. The need to conduct research in a microgravity environment is very clear. Because of the relatively large size of the basic structures, gravitational forces can dominate and cause sedimentation, convective flows, and other property gradients. The weaker forces such as surface tension and entropic forces are completely masked on earth. In granular materials, stresses and yield properties are also sensitive to gravity.

Soft Condensed Materials

A series of experiments in soft condensed materials (colloids) conducted on the International Space Station (ISS) provide a unique opportunity to explore fundamental physics and to gather data needed to push the frontiers in colloidal engineering. Colloids are small enough that they behave much like atoms and can be used to model their behavior. Their size, shape, and interactions enable us to control them, hence their importance in industry. Paints, aerosols, and foams are examples of manufactured colloidal mixtures. Colloids also appear frequently in nature (e.g. milk). Understanding the properties of colloids should help scientists to specifically engineer them for the manufacture of new materials and products and to provide better control for existing products. One example is the perfection of stabilizers. These play a significant role in many multibillion dollar industries. The gravitational effects of sedimentation and convection have distorted these measurements in the past, and with this mask removed, we are able to refine our understanding of phase separation.

Physics of Colloids in Space (PCS)

The PCS flight experiment was designed to study the phase behavior, growth dynamics, morphology, and mechanical properties of different types of colloidal suspensions; including binary colloidal alloys, colloidal polymer mixtures, fractal colloidal aggregates, and the natural entropy driven transition from a disordered glassy state to an ordered crystalline one. In the first two areas mentioned, many basic questions about phase diagrams, thermodynamic stability, and phase transformation kinetics were answered. Detailed information about the structure and properties of fractal aggregates was obtained over a much wider range of measurement with more relevant conditions than possible on earth.

Binary Colloidal Alloy Tests (BCAT)

The BCAT-3/4/5/6 experiments were a set of notebook size science investigations each containing 10 samples. Once in microgravity on the International Space Station (ISS), these samples were individually mixed until their structure was randomized, and they were then photographed as they evolved. Several different types of science questions were addressed and refined with each BCAT flight. When scientists learned something new from one BCAT experiment, they often chose to use a later BCAT flight to address these puzzles or to narrow down the number of possible interpretations.

The BCAT experiments on seeded-growth (Paul Chaikin and Andrew Hollingsworth - NYU) have shown us that glassy (completely disorder) samples will crystallize in new ways in the absence of gravitational sedimentation and jamming. [5] They showed that certain samples will crystallize in space but not on earth. What we don't yet know is just how important the seed particles are in making this happen. The upcoming BCAT-C1 experiment (sponsored by CSA) will fly three samples with different concentrations of seed particles (including one sample with no seed particles) to help quantify this effect. Being able to use seed particles to control nucleation was computationally predicted to work; thanks to the BCAT experiment, we have confirmed this, what remains now is to quantify this technique. Microgravity allows us to have both index matching (for clarity) and density matching (to avoid sedimentation in normal gravity).

Another theme in the BCAT experiment is the study of phase separation with model critical fluid samples on the ISS. These model systems do not have the difficult micro-Kelvin temperature control issues of traditional critical fluids, and they serve as a model system for understanding ideal systems formed from particles that are all the same size (monodisperse) and whose attractive force can be adjusted by the addition of a polymer. Depletion attraction is used to provide a clever way of setting the "effective" attractive force between particles.

From these studies, it was found that the position of the critical point is not where the literature suggests it

should be, based on observing phase separation in the presence of gravity. A series of samples were created covering a wide range, to capture behavior deep in the phase-separating region (i.e. samples that would phase separate on the ground) as well as in the non-phase separating region---based on observations on the ground. On ISS, all of the samples did phase separate, demonstrating that initial estimates of the position of the phase boundary and critical point (above which phase separation does not occur) are quite far off, and that true microgravity environments are needed to probe these physics.

A number of new measurements relating to the rate of phase separation were also obtained. The classic experiments showing spinodal decomposition took minutes to complete; an earlier experiment by Bailey et al. [6] using PCS phase separated in a matter of hours. By contrast, BCAT samples phase separate in days to weeks, much longer than even a Space Shuttle flight, demonstrating the importance of the stable, microgravity laboratory present with ISS. The investigators were thus able to confirm phase separation, in terms of the rate of growing length scales, as theory and previous experiments have predicted---but in a regime an order of magnitude smaller than has been previously shown. Being able to pinpoint the positions of these samples in a phase diagram and recording the rates of phase separation should enable theorists to enhance their models and understanding of these simple textbook systems.

On-going BCAT experiments, are addressing more complex multicomponent (polydisperse) phase separation and gelation samples (Matthew Lynch and Thomas Kodger – Proctor and Gamble – P & G). The goal of the BCAT-6-Gelation experiments is to understand the impact of particulate size distribution on the aging of gels and on late collapse. These studies are expected to provide improved methods for the production of gels, enhancing shelf life and quality, while lowering production cost for a wide variety of commercial products. For P & G, a better understanding of stabilizers is likely to have a significant impact on a multi-billion dollar business.

The focus of the Simon Fraser University "Compete" Samples (Barbara Frisken and Arthur Bailey – SFU / CSA) is the effect of phase separation on crystal growth. On Earth, gravity causes the colloids to settle, making such a study particularly difficult. Performing these experiments in the microgravity environment of the International Space Station is enabling scientists to study growth of much larger structures, and, thus, maximize the extent to which the behavior can be explored. Improved understanding of these processes will lead to more refined manufacturing processes and commercial products. The competition between a phase separation process and an order-disorder transition remains largely unstudied and offers an opportunity to observe some fascinating behavior. This has led to the upcoming BCAT-C1 flight experiment that will devote 7 of its 10 samples to exploring this new phenomenon. The overarching goal of all these experiments is to develop the key knowledge to help make colloidal engineering a reality. In addition, this experiment is helping scientists understand the fundamental properties of colloid-polymer mixtures to further improve the commercial use of such systems.

Advanced Colloids Experiment (ACE)

Fundamental studies of order and frustration, including the role of colloidal particle shape on structure and complex processes, such as self-assembly, motility, and non-biological self-replication are key research areas to address using the Light Microscopy Module (LMM), a powerful and versatile microscopy facility.

The Advanced Colloids Experiment (ACE) and LMM allow scientists to process, manipulate, and characterize colloidal samples in micro-gravity environment available on the International Space Station (ISS). The near absence of gravitational settling and particle jamming enables scientists to not only study nucleation, crystallization, self-assembly and micro rheology but also active manipulation of such phenomena.

To meet this goal, the ACE experiment will be conducted in stages, with the availability of confocal microscopy being the ultimate aim. The first portion of the microscope's capabilities to be made available to colloids scientists is called ACE-1 and was just recently launched. This will feature a microscope that supports epi-illumination (lighting from above) along with a simple white-light LED available for back-lighting. When ACE-2 becomes available in 2014, a condenser will provide trans-illumination (light from below) with 100x magnification for oil-immersion optics. ACE-2 will also provide sample cells with more sophisticated temperature control and electric-field allowing study of new class of phenomena on ISS.

For ACE-3 in 2016, the addition of confocal microscopy (a confocal head, a confocal camera, and a laser), enabled 3D imaging. The ultimate goal of the ACE science and engineering team is to return data of sufficient accuracy, precision, and quantity to determine the crystal structure, lattice constant (crystal) to 0.5% accuracy. The nucleation and growth rates for all phases shall be determined to 10% accuracy. The cooperative diffusion coefficient (liquid and glass), the elastic constant (crystal and glass), and the dynamic viscosity (crystal and glass) shall be determined to a 10% accuracy. The average root mean square displacement (crystal)

shall be determined to 2% accuracy; the particle positions of tracer particles to 1 nanometer; the particle volume fraction to 0.5%.

Rheology and Morphology of Complex Fluids

Newtonian fluids can be characterized by a single coefficient of viscosity for a specific temperature. Although this viscosity will change with temperature, it does not change with the flow rate or strain rate. Only a small group of fluids exhibit such constant viscosity, and they are known as Newtonian fluids. A large class of fluids where the viscosity changes with the strain rate (or relative velocity of flow) are called non-Newtonian fluids. Rheology generally accounts for the behavior of non-Newtonian fluids by characterizing the minimum number of functions that are needed to relate stresses with rate of change of strains or strain rates.

Investigating the Structure of Paramagnetic Aggregates From Colloidal Emulsions (InSPACE)

Magnetorheological (MR) fluids are suspensions of small (micron-sized) superparamagnetic particles in a nonmagnetic medium. These controllable fluids can quickly transition into a nearly solid-like state when exposed to a magnetic field and return to their original liquid state when the magnetic field is removed. Their rheological properties can be controlled by controlling the strength of the magnetic field. Due to the rapid-response interface that they provide between mechanical components and electronic controls, MR fluids can be used to improve or develop new brake systems, seat suspensions, robotics, clutches, airplane landing gear, and vibration damping systems.

The goal of InSPACE, conducted on ISS, was to determine the true three-dimensional low-energy (equilibrium) structure of an MR emulsion in a pulsed magnetic field. The microstructure of MR fluids plays a significant role in determining their bulk rheological properties. InSPACE conducted a microscopic video study of the MR fluid in a pulsed magnetic field to determine the effect of varying magnetic field, pulse frequency, and particle size on the equilibrium microstructures. The low gravity environment, provided on the ISS, eliminates the effects of sedimentation which otherwise becomes significant for these relatively large aggregate structures. A pulsed field was used to investigate lowest energy state structures. A pulsed field permits particle rearrangement, via diffusion when the field is off, such that the suspension can adopt a lower energy state structure.

Shear History Extensional Rheology Experiment (SHERE)

SHERE was designed to investigate the effect of pre-shearing (rotation) on the stress and strain response of a polymer fluid (a complex fluid containing long chains of polymer molecules) being stretched in microgravity. This information is particularly relevant for understanding the deformation and evolution of non-Newtonian thin fluid columns (threads) in a wide variety of industries, including fiber spinning, injection molding, or food and consumer product processing.

In a microgravity environment, the absence of gravitational body forces acting on the deformable fluid permits a large increase in the radial dimension of the initial liquid bridge. By increasing the initial radius, the viscous force is increased, and the time-evolution in the tensile force becomes slow enough to be measurable for extended times. This allowed the long dynamics of the filament thinning to be monitored on ISS. A stable microgravity environment enabled the understanding of the effect of the initial conditions at the end of the stretching phase on the capillary thinning and time to breakup. Analysis of the experimental data from SHERE on ISS revealed interesting elastic instabilities on the free surface of the fluid sample. The data showed the formation of beads-on-a-string structures in the absence of gravitational sagging. The development and evolution of such phenomena upon cessation of elongation have not yet been described.

FLUID PHYSICS

The Fluid Physics discipline which focuses on gravity-dependent research issues includes two major sub-disciplines. The first sub-discipline is multiphase flows (with and without heat transfer). Under this area, disciplines included are two-phase flow; phase separation; boiling and condensation; flow through porous media; system stability; bio-fluids; and storage and handling of fluids (cryogenics). The second sub-discipline is interfacial phenomena. Within this area, disciplines include capillary flow; dynamics; and instabilities. Even though these studies are categorized into two major sub-disciplines, it should be noted that in most cases there is significant overlap. For example, it is difficult to ignore interfacial forces when studying storage and handling or two-phase flow through porous media.

Boiling Experiment Facility (BXF)

BXF accommodated two separate investigations, the Microheater Array Boiling Experiment (MABE) and the Nucleate Pool Boiling Experiment (NPBX), to examine fundamental boiling phenomena. Both experiments on the BXF were used to validate predictive models being developed for heat transfer coefficients, critical heat flux, and the pool boiling curves.

The objective of MABE was to determine the local boiling heat transfer mechanisms in microgravity for nucleate and transition boiling and the critical heat flux. Specially designed microheaters (0.1mm x 0.1mm or 0.27mm x 0.27mm) operated at a constant temperature minimizing the amount of lateral heat conduction between them. Because of their small size, both temporal and spatial power measurements were made for each microheater, and were synchronized with the position of the liquid and vapor adjacent to the instrumented microheaters. Each microheater is on the order of the bubble departure size in normal gravity, but significantly smaller than the bubble departure size in reduced gravity. The boiling process was visualized from the side and through the bottom of the transparent MABE microheater arrays. Data from this high quality microgravity data was used to refine the scaling parameter for heat flux with gravity, which was primarily based on parabolic flight experiments. The robustness of this framework in predicting low gravity heat transfer is further demonstrated by predicting many of the trends in the pool boiling literature that cannot be explained by any single model.

The other experiment, NPBX, selectively activated nucleation sites in order to understand bubble growth, detachment, and subsequent motion of single and large merged bubbles under reduced-gravity conditions. The results of these experiments showed that a single bubble continues to grow to occupy the size of the chamber without departing the heater. During lateral merger of bubbles, at high superheats, a large bubble may lift off from the surface, but continues to hover near the surface. Neighboring bubbles are continuously pulled into the large bubble. At low superheats, bubbles at neighboring sites simply merge to yield a larger bubble. The larger bubble mostly locates in the middle of the heated surface and serves as a vapor sink. The latter mode continues to persist when boiling is occurring all over the heater surface. Steady state nucleate boiling and critical heat fluxes are found to be much lower than those obtained under earth normal gravity conditions. The data is now being used for calibration of results of numerical simulations. Any correlations that are developed for nucleate boiling heat transfer under microgravity condition must account for the existence of vapor escape path (sink) from the heater, size of the heater, and the size and geometry of the chamber.

The IntraVenous Fluid Generation (IVGEN)

IVGEN experiment was recently flown on the ISS with funding from the Human Research Program. This was a successful technology demonstration experiment to take ISS potable water, purify it through the use of a packed bed with a deionizing resin, mix the water uniformly with salt to generate a Normal Saline solution that met the United States Pharmacopeia for salt concentration, impurities and sterility. Specific two-phase technologies that were incorporated included membrane-based air-water separators, conductivity probes, and a packed bed.

Dynamics, Instabilities and Interfacial Phenomena

Fluid dynamics, instabilities and interfacial or capillary flow are another very important subset of fluid physics. Recent experiments flown on the ISS include the Capillary Flow Experiment (CFE) which was a suite of experiments that investigated capillary flows and flows of fluids in containers with complex geometries. Results will improve current computer models that are used by designers of low gravity fluid systems, and will lead to improved fluid transfer systems on future spacecraft. Follow-on experiments are planned to study additional geometries as well as other variables such as different fluids.

Constrained Vapor Bubble (CVB)

In satellites used for communications, global positioning systems, and defense purposes, a heat pipe is the device used to regulate temperature and keep the overall systems operating reliably. A heat pipe is a simple device that can efficiently transfer heat from a hot spot to a cooler remote location without the use of a mechanical pump. To further insights into the operation of a heat pipe in space, scientists launched an investigation called the Constrained Vapor Bubble (CVB) to the International Space Station. The CVB is the prototype for a wickless heat pipe and was the first full-scale fluids study in the Fluids Integrated Rack or FIR facility flown on the U.S. module of the space station. The Constrained Vapor Bubble (CVB) is a prototype for a wickless heat pipe that was studied in the microgravity environment of the International Space Station. It is both an experiment in basic thermal fluid science and a study of an extended fin heat exchanger. The CVB consists of a relatively simple setup – a quartz cuvette with sharp corners partially filled with pentane as the working fluid. Along with temperature and pressure measurements, the two-dimensional thickness profile of the pentane menisci formed at the corners of the cuvette were determined using the Light Microscopy Module (LMM) in the Fluids Integrated Rack (FIR). The flow processes within the device were visualized in a way not possible before. Microscopic and macroscopic scale data collected from the experiment enhances the understanding of the fundamental processes in boiling, evaporation, condensation, and adsorption in both earth and microgravity environments.

Results from the experiment [7], [8] indicated that the CVB operates at higher pressures and temperatures in microgravity, a consequence of radiation being the only mechanism for removing heat from the device. The temperature profile data along the heat pipe and corresponding heat transfer calculations demonstrated that CVB performance is enhanced in the microgravity environment due to increased capillary flow even though heat transfer to the external environment is diminished by the absence of natural convection. Image data of the liquid profile in the grooves of the heat pipe indicated that the curvature gradient is considerably different from that on Earth and supports the conclusion that capillary flow and internal heat transfer are increased. Operations with the 20 mm version of the device allowed us to view explosive nucleation within the CVB upon device start-up. In this scenario, bubble nucleation occurred spontaneously and periodically at the hot end of the device. The newly formed bubble returned to its original size, shape and location as heat loss from the CVB re-established the original, pseudo-steady-state temperature and pressure profiles.

Capillary Flow Experiments (CFE)

The CFE includes a suite of fluid physics flight experiments that investigate capillary flows in low gravity [9], [10], [11]. The CFE data is crucial to the Space Exploration Initiative particularly pertaining to fluid management systems including fuels/cryogen storage, thermal control, water recycling, and materials processing. CFE is a simple fundamental scientific study that have yielded quantitative results from safe, low-cost, short time-to-flight, hand-held fluids experiments. The experiments provide critical results for capillary flow that cannot be achieved in ground-based tests. These include: 1) Dynamic effects associated with a moving contact boundary condition; 2) Capillary driven flow in interior corner networks; and 3) Critical wetting phenomena in complex geometries.

The CFE experiments consist of three different geometric configurations: the Interior Corner Flow (ICF), the Vane Gap (VG), and the Contact Line (CL) experiments. The ICF experiment investigates propellant management and passive capillary flow in tapered geometries for which boundary conditions are not well understood or modeled. The VG experiment scrutinizes the critical wetting condition when interior corners do not actually make contact, in particular the corner and gap formed by an interior vane and the interior wall of a propellant tank, or between the intersections of vanes in a complex vane network. The CL experiment studies the impact of the dynamic contact line. The contact line controls the interface shape, stability, and dynamics of capillary systems in low-g. These experiments provide a direct measure expected behavior assuming either a free or pinned contact line condition. The two CL units are identical except for their respective wetting characteristics.

The Capillary Flow Experiments–2 (CFE-2) was a continuation of the CFE experiments. Presently four reflight units have been operated on ISS. The ICF1 and ICF2 units have different volumes and viscosities of the test fluid. The VG1 and VG2 units have perforated vanes, as opposed to solid vanes for CFE.

For the CL experiments, over 350 primary and extra science events have been reduced to date, where significant contributions include both experimental results and numerical comparisons. The complete database may be found at http://cfe.pdx.edu. To date, the damped interface oscillations (frequency and decay) as functions of fluid properties, wetting, contact line condition, disturbance type, and amplitude have been pursued.

For the VG experiments, the critical wetting angles have been measured to within ±0.5°, nearly four times more accurate than planned. In addition, a bulk shift phenomena has been discovered that has implications for spacecraft tank design asymmetries.

Capillary Channel Flow (CCF)

The Capillary Channel Flow (CCF), developed jointly by DLR and NASA, was flown on the ISS. This is a versatile experiment for studying a variety of inertial-capillary dominated flows, key to spacecraft systems that cannot be studied on the ground. Because hydrostatic pressure is absent in microgravity, technologies for liquid management in space use capillary forces to position and transport liquids. On earth, the effect of capillary forces is limited to a few millimeters. In space, these forces still affect free surfaces that extend over meters. For the application of open channels in propellant tanks of spacecraft, design knowledge of the limitations of open capillary channel flow is imperative. These limitations are based on the restriction that the liquid fuel must be free of bubbles prior to entering the thrusters.

CCF examined flows in parallel plate channels, grooves, and interior corner capillary conduits. These geometries represent a class of practical capillary geometries that are implemented in designs of the fuels and tank community of the aerospace industry. Current spacecraft fluid processing equipment is replete with such constructs. Validation of theoretical models developed for such geometries is expected to lend confidence to the application of theory to other geometries pertinent to advanced microgravity fluid systems development.

The test matrix for Experimental Unit #1 (EU#1), which included the parallel plate and groove channel

geometries, was completed in March 2011. Over 1300 data points were collected with 900 consisting of high speed, high resolution video image (100+ GB of video data). Preliminary data analysis has verified model predictions for a number of critical conditions (where the maximum flow rate occurs). Preliminary results indicate several "new" unstable conditions were discovered which do not appear to match existing theoretical models.

The test matrix for Experimental Unit #2 (EU#2), which included the wedge channel geometry, was completed in October 2011. Nearly 3000 test points were completed, including high speed and standard video imaging. Data reduction has begun on the critical flow rate data in the wedge geometry. Three preliminary flow regime maps have been generated that identify the passive gas/liquid separation regimes for the wedge channel geometry.

CONCLUSION

The past 12 years have shown tremendous success in ISS research in the Combustion Science, Complex Fluids, and Fluid Physics, disciplines. This research balances the need for investigations that contribute to NASA Exploration goals, and solve terrestrial problems to produce societal benefit. Planned research on the ISS in the next few years will see a number of new experiments exploring areas such as two phase flow through porous media; gaseous flame structure and soot properties, an experiment to model complex interactions among two-phase transport mechanisms and the phase change phenomena that control long-term propellant storage tank pressurization and control in microgravity; solid material flammability; suspended liquid crystals; fire detection; and the rheology of foams to name a few.

REFERENCES

1. Nayagam, V, Dietrich, D. L., Ferkul, P.V., Hicks, M.C., Williams, F.A., "Can cool flames support quasi-steady alkane droplet burning?", Combustion and Flame, in-press 2012.
2. Dotson, K. T., P. B. Sunderland, Z. G. Yuan, D. L. Urban, 'Laminar Smoke Points of Coflowing Flames in Microgravity," *Fire Safety Journal* 46, 2011, pp. 550–555.
3. Urban, D.L. Griffin, D., Ruff, G.A., Cleary, T., Yang, J., Mulholland, G.W., Yuan, Z.G., Detection of Smoke from Microgravity Fires, SAE Transactions, pp 375-384, 2005.
4. Urban, D., Ruff, G., Greenberg, P., Mulholland, G., Cleary, T., Yang, J., Yuan, Z., Bryg, V., Particle Morphology and Size Results from the Smoke Aerosol Measurement Experiment-Reflight, 42nd International Conference on Environmental Systems (ICES), San Diego, CA, July 16-19, 2012.
5. Wang, Ton, Ruojie Sha, Rémi Dreyfus, Mirjam E. Leunissen, Corinna Maass, David J. Pine, Paul M. Chaikin, and Nadrian C. Seeman, "Self-replication of Information-bearing Nanoscale Patterns," Nature 478, October 13, 2011, pp. 225–228.
6. Bailey, A. E., W. C. K. Poon, R. J. Christianson, A. B. Schofield, U. Gasser, V. Prasad, S. Manley, P. N. Segre, L. Cipelletti, W. V. Meyer, M. P. Doherty, S. Sankaran, A. L. Jankovsky, W. L. Shiley, J. P. Bowen, J. C. Eggers, C. Kurta, T. Lorik, Jr., P. N. Pusey, and D. A. Weitz, "Spinodal Decomposition in a Model Colloid-Polymer Mixture in Microgravity," Physical Review Letters 99, 205701, 2007.
7. Chatterjee, Arya, Joel L. Plawsky, Peter C. Wayner, Jr., David F Chao, Ronald J Sicker, Tibor Lorik, Louis Chestney, John Eustace, and John Zoldak, "The Constrained Vapor Bubble Experiment for ISS – Earth's Gravity Results," AIAA Journal of Thermophysics and Heat Transfer, 2010 vol. 24 no. 2, April 2010.
8. Chatterjee, Arya, Joel L. Plawsky and Peter C. Wayner, Jr., David F Chao, Ronald J Sicker, Tibor Lorik, Louis Chestney, John Eustace, Raymond Margie, John Zoldak "The Constrained Vapor Bubble Experiment Fin Heat Pipe in Microgravity," Industrial & Engineering Chemistry Research, February 25, 2011.
9. Chen, Y., M. M. Weislogel, and C. Nardin, "Capillary-driven flows along rounded interior corners," J. Fluid Mech. Vol. 566, pp. 235-271, (2006).
10. Weislogel, M. M., J. A. Baker, R. M. Jenson, "Quasi-steady capillary-driven flows in slender containers with interior edges," J. Fluid Mechanics, vol. 685, pp. 271-305, 2011.
11. Weislogel, M. M., Y. Chen, D. Bolleddula, "A Better Non-Dimensionalization Scheme for Slender Flows: The Laplacian Operator Scaling Method," Physics of Fluids 20, 093602 (2008).